ANISOTROPIC SURFACE FUNCTIONALIZATION AND APPLICATIONS OF UPCONVERSION NANOPARTICLES

By

Wei Ren

Institute for Biomedical Materials & Devices

School of Mathematical and Physical Sciences, Faculty of Science

Supervisors:

Prof. Dayong Jin & Dr. Gungun Lin

UNIVERSITY OF TECHNOLOGY SYDNEY

This thesis is presented for the degree of Doctor of Philosophy

December 2018

Certificate of Original Authorship

I, Wei Ren, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mathematical and Physical Sciences, Faculty of Science, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Date: 15/12/2018

Acknowledgements

Firstly, I would like to thank my supervisor Prof. Dayong Jin who provided me with the opportunity to be a PhD candidate in Australia and who then greatly supported my research work over the last four years. Without him, I could not imagine completing this undertaking. Jin devoted himself to the development of my work in his research group and kept it on track. In July of 2015, when we relocated to the University of Technology Sydney, we started with almost no facilities. Jin sought funding for this and kept us focused. In the past three years, I witness the establishment of the Institute for Biomedical Materials & Devices (IBMD) and the ARC Research Hub for Integrated Device for End-user Analysis at Low-levels (IDEAL) under his leadership. Supervised by Jin, I learned how to undertake a research project logically and solve problems and overcome challenges. I also benefited from his help with academic writing. Besides research, he encouraged me to optimistically meet the challenges in my life. I learnt how to communicate and collaborate with other researchers. His attitude to research as well as to life will continue to inspire me.

Next, I would like to acknowledge my colleagues and collaborators who contributed to my research. Thanks to Dr. Jie Lu for sharing his research experience, Dr. Shihui Wen for providing me with upconversion nanoparticles at a high constant quality, Dr. Gungun Lin for improving the illustrations in my publications, Dr. Qian Peter Su and Dr. Lining Arnold Ju for their super-resolution imaging, Dr. Sherif Abdulkader Tawfik and Prof. Michael J. Ford for their fantastic simulation work, Mr. Hao He and Ms. Yingzhu Zhou for their time-consuming cell culture, and Dr. Fan Wang and Mr. Zhiguang Zhou for building up the laser scanning confocal microscope. Professor Antoine van Oijen, Dr. Harshad Ghodke, and Ms. Li Wang from the University of Wollongong and Dr. Deming Liu and Mr. Christian Clark from the University of Technology Sydney also provided their valuable support for my research. I would also like to thank Dr. Tom Lawson for proof-reading my thesis.

Thanks very much to my dear friends I met in Australia, who provided my life with colour. These include Mr. Hao He, Mr. Chao Mi, Mr. Ming Guan, Dr. Baljeet Singh Rana, Mr. Juan Adrian Gaona Moscoso, and Ms. Racheal Zhao.

I worked as a research assistant in UTS since early 2016. This work has filled me up with joy as I solve problems for the group. Our school manager Elizabeth Gurung Tamang, project administrator Lucia Kralova and school administration officer Klara Janickova provided me with much guidance and help. I would like to say thank you to them as well.

On the 5th of January 2015, my wife gave birth to our son Jiade (Jared) Ren at a time when I was still in Australia working on this thesis. I greatly love my wife and my parents and thank them for bringing up my son and supporting my work overseas. They sacrificed much for me and for my son in the past four years. I promise to now spend more time with my beloved family.

Finally, I would like to acknowledge the China Scholarship Council and the Faculty of Science, UTS. They supported my tuition fees as well as my living expenses. I appreciate in the support I received from both China and Australia. I do wish the friendship of these two great countries will last forever.

Format of Thesis

This thesis follows the conventional format of seven chapters. The relationship between these chapters is shown in the flowchart below.

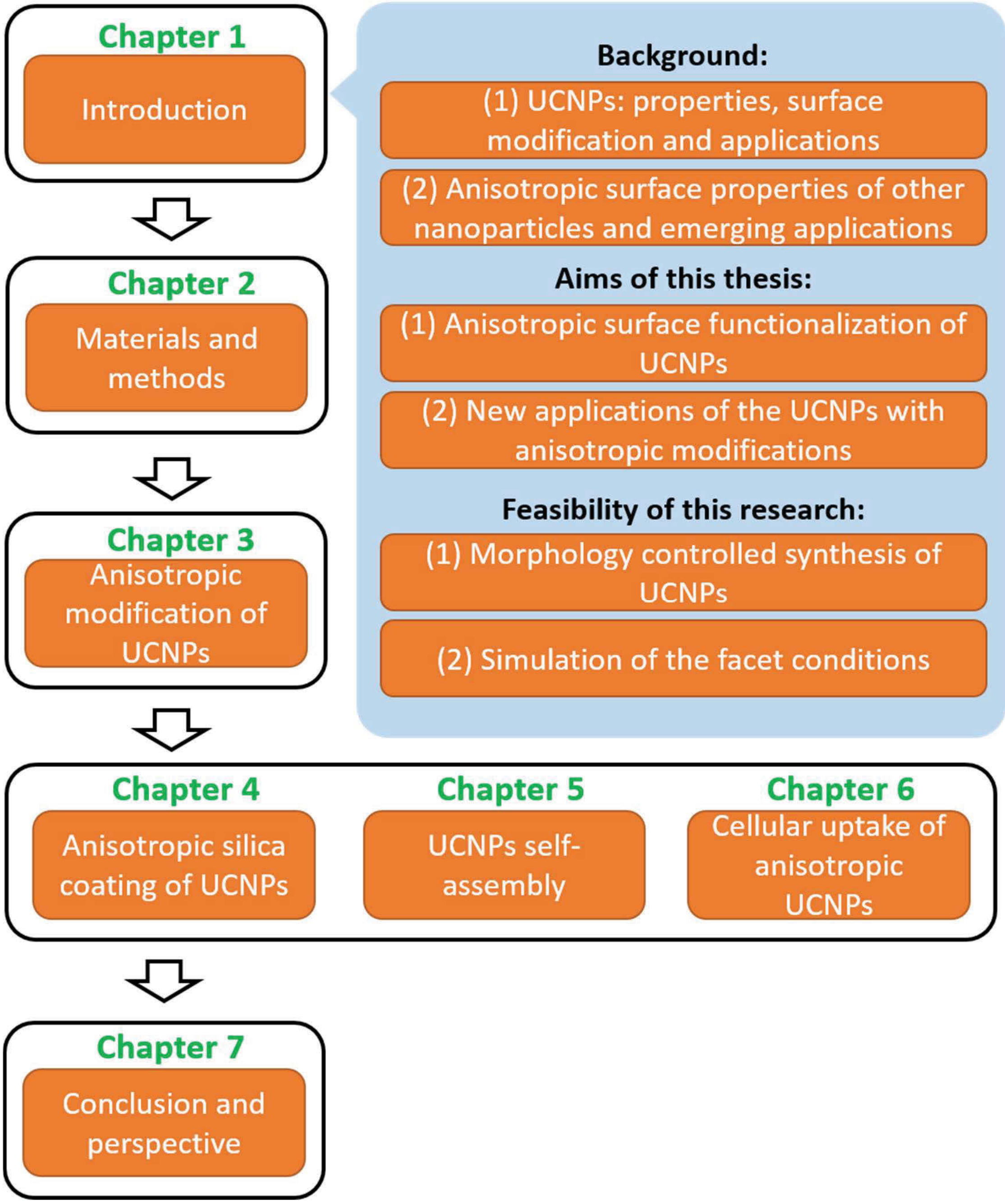
Chapter 1 is the introduction chapter, and is composed of three sections. The first section describes the unique optical properties of upconversion nanoparticles (UCNPs), the surface modification strategies used to functionalize these particles so that they can act as fluorescent probes, and lists a range of their applications. The second section reviews the current progress in fabricating anisotropic surface properties in other types of nanoparticles and their potential application. For example, facet-selective silica coating, their controllable self-assembly, and their cellular uptake. These two sections provide the research inspiration of this thesis to study the anisotropic surface properties of UCNPs and explore and test new methods for generating controlled anisotropic surface properties on UCNPs. To test the feasibility of this thesis plan, the last section in the thesis describes my participation in a project to develop UCNPs with highly controlled morphology using a computational simulation of the surfactant-surface interaction at different facets on these particles. Further background knowledge relevant to the thesis topic is also included in this last section of this chapter.

Chapter 2 provides detailed information of the materials, preparation and characterization methods used to produce data described in the result chapters.

Chapter 3 provides the experimental foundation for the thesis by studying the facet-selective ligand exchange of DNA molecules onto UCNPs.

Chapters 4, 5 and 6 further apply the knowledge obtained from Chapter 3 in three areas of applications, including (1) facet-selective silica coating, (2) their self-assembly, and (3) the cellular uptake of UCNPs with isotropic and anisotropic surface functionalizations.

Finally, the research results are summarised in Chapter 7. Potential future developments and applications using the new knowledge gained in this thesis along the directions indicated (primarily by Chapters 5 and 6) are summarised.


Chapter 1
Introduction
Background:
(1) UCNPs: properties, surface modification and applications
(2) Anisotropic surface properties of other nanoparticles and emerging applications
Aims of this thesis:
(1) Anisotropic surface functionalization of UCNPs
(2) New applications of the UCNPs with anisotropic modifications
Feasibility of this research:
(1) Morphology controlled synthesis of UCNPs
(2) Simulation of the facet conditions
Chapter 2
Materials and methods
Chapter 3
Anisotropic modification of UCNPs
Chapter 4
Anisotropic silica coating of UCNPs
Chapter 5
UCNPs self-assembly
Chapter 6
Cellular uptake of anisotropic UCNPs
Chapter 7
Conclusion and perspective

List of Publications

Research Papers:

[1] J. Lu, Y. Chen, D. Liu, **W. Ren**, Y. Lu, Y. Shi, J. A. Piper, I. Paulsen, and D. Jin, One-step protein conjugation to upconversion nanoparticles, *Analytical Chemistry*, 2015, **87**, 10406-10413.

[2] X. Zheng, Y. Lu, J. Zhao, Y. Zhang, **W. Ren**, D. Liu, J. Lu, J. A. Piper, R. C. Leif, X. Liu, and D. Jin, High-precision pinpointing of luminescent targets in encoder-assisted scanning microscopy allowing high-speed quantitative analysis, *Analytical Chemistry*, 2016, **88**, 1312-1319.

[3] D. Liu, X. Xu, Y. Du, X. Qin, Y. Zhang, C. Ma, S. Wen, **W. Ren**, E. M. Goldys, J. A. Piper, S. Dou, X. Liu, and D. Jin, Three-dimensional controlled growth of monodisperse sub-50 nm heterogeneous nanocrystals, *Nat Commun*, 2016, **7**, 10254.

[4] L. Wang, L. Ren, D. Mitchell, G. Casillas-Garcia, **W. Ren**, C. Ma, X. X. Xu, S. Wen, F. Wang, J. Zhou, X. Xu, W. Hao, S. X. Dou, and Y. Du, Enhanced energy transfer in heterogeneous nanocrystals for near infrared upconversion photocurrent generation, *Nanoscale*, 2017, **9**, 18661-18667.

[5] J. Zhou, S. Wen, J. Liao, C. Clarke, S. A. Tawfik, **W. Ren**, C. Mi, F. Wang, and D. Jin, Activation of the surface dark-layer to enhance upconversion in a thermal field, *Nature Photonics*, 2018, **12**, 154-158.

[6] **W. Ren**, S. Wen, S. A. Tawfik, Q. P. Su, G. Lin, L. A. Ju, M. J. Ford, H. Ghodke, A. M. van Oijen, and D. Jin, Anisotropic functionalization of upconversion nanoparticles, *Chemical Science*, 2018, **9**, 4352-4358.

[7] **W. Ren**, Y. Zhou, S. Wen, H. He, G. Lin, D. Liu, and D. Jin, DNA-mediated anisotropic silica coating of upconversion nanoparticles, *Chemical Communications*, 2018, **54**, 7183-7186.

[8] M. Guan, Z. Zhou, L. Mei, H. Zheng, **W. Ren**, L. Wang, Y. Du, D. Jin, and J. Zhou, Direct cation exchange of surface ligand capped upconversion nanocrystals to produce strong luminescence, *Chemical Communications*, 2018, **54**, 9587-9590.

Conference Presentations:

[1] **W. Ren**, S. Wen, D. Liu, L. Fu, J. Lu, and D. Jin, The anisotropic surface properties of upconversion nanocrystals, *International Conference on Nanoscience and Nanotechnology 2016*.

[2] **W. Ren**, S. Wen, H. He, Q. P. Su, S. A. Tawfik, H. Ghodke, F. Wang, M. J. Ford, A. van Oijen, and D. Jin, Facet selective ligand competition and functionalization on anisotropic nanocrystals, *International Conference on Nanoscience and Nanotechnology 2018*.

Contents

Abstract

Lanthanide-doped upconversion nanoparticles (UCNPs) step-wise convert near-infrared adsorbed light into visible emitted light. Monodispersed UCNPs have a large anti-Stokes shift, sharp emission and long excited-state lifetimes. The controlled synthesis of their heterogeneous nanostructures can create different morphologies with different properties. This makes it possible to use these particles to perform biomolecular assays, multi-scale and multi-modal imaging, as well as targeted delivery of drugs for nanoscale therapies. To make these inorganic nanomaterials practically useful, their surfaces require functionalization with active chemical groups that target important specific biomolecular and cellular structures within the body.

Current literature assumes UCNPs are spherical in shape and that isotropic surface modification strategies such as ligand oxidation, amphiphilic ligand interaction (insert), ligand exchange, and silica coating techniques are sufficient for their surface modification. In this thesis, the author explores the surface coverage at the nanoscale of a library of non-spherical rods, discs, and dumbbell structures of UCNPs, and demonstrates that different facets of nanocrystals can be selectively modified by DNA and surfactant molecules, and silica coating layers. This results in the creation of anisotropic surfaces on these particles, i.e. one where nanocrystals can have either/both hydrophilic or/and hydrophobic surfaces depending on their facet arrangement. It is hoped that outcomes from this research advance understanding of nanoscale surface chemistry and introduce a series of surface modification techniques that could lead to new uses for these particles. The addition of anisotropic silica coating and controllable self-assembly of nanocrystal building blocks could also lead to tailored efficiency and behaviours in the cellular uptake of this new class of nanoparticles.

Chapter 1 summarises the unique optical properties of UCNPs techniques used for their surface modification methods and their many uses. This chapter lists current literature that reports on the anisotropic surface properties of other nanoparticles such as gold nano-rods, and their potential usefulness. This leads to the inspiration for this thesis and a description of its four-specific research goals. To justify the feasibility of its hypothesis, that is, that different crystalline facets result in different anisotropic surface properties of UCNPs with unique behaviours, this chapter describes some preliminary studies that the author was involved that led to the work described in this thesis. Specifically, the author's work on the controlled synthesis of non-spherical UCNPs and the computational simulation of their surface properties and their calculated interactions with common surfactant molecules.

Chapter 2 provides a detailed description of the materials, preparation and characterization methods used in the work described in this thesis.

Chapter 3 reports on a simple “mix-and-shake” method to selectively modify the facets of UCNPs by the addition of synthetic DNA molecule strands, with or without the phosphate group at the ends of these molecules. A range of characterization techniques were then described to verify that the different facets of these UCNPs were tailored to have hydrophobic and hydrophilic surface properties, enabling their usefulness in a range of interesting applications described in the three chapters that are next.

Chapter 4 describes a method that enabled the addition of an anisotropic silica coating onto a range of UCNPs that have various shapes. The addition of this coating can be switched on/off by controlling the surface conditions of the particles using the facet-selective modification of DNA molecules. According to the results described, silica shell was only deposited onto UCNP facets that had not undergone DNA modification, regardless of the specific morphology of the UCNPs tested. In this chapter, the feasibility, mechanism, and reproducibility of this coating approach were provided.

Chapter 5 describes the technique used for the controlled self-assembly of UCNPs and their hybrid structures. Both side-by-side and end-to-end self-assembly of rod-shape UCNPs structures were reported. Moreover, an end-to-end pattern of self-assembly technique was reported that created a hybrid structure with gold nanoparticles in between of pairs of UCNP, forming a one-dimensional chain structure. In this chapter, the conditions for obtaining these self-assembly structures were described.

Chapter 6 describes the evaluation of the different behaviours of UCNPs that possess different isotropic and anisotropic surface properties with regard to their cellular uptake. An improved efficiency in this uptake was observed in UCNPs with anisotropic surface properties, and this suggests a new controllable feature for their use in drug delivery applications.

The results reported in this thesis provide a new understanding of the surface properties of UCNPs. A possible outcome of this work is a new range of uses for this particle technology through the precise control of their surfaces.

Keywords: upconversion nanoparticles, surface modification, anisotropic surface properties, nanocrystal facets, silica coating, self-assembly, cellular uptake

List of Acronyms

(in alphabetic order)

DNA	Deoxyribonucleic Acid
DFT	Density Functional Theory
NH_4OH	Ammonium Hydroxide
OA	Oleic Acid
OA^-	Oleate Anions
OAH	Oleic Acid Molecule
ODE	Octadecene
OM	Oleylamine
RE	Rare Earth Elements
STORM	Stochastic Optical Reconstruction Microscopy
TEM	Transmission Electron Microscopy
TEOS	Tetraethyl Orthosilicate
UCNPs	Upconversion Nanoparticles